Modeling Surface Transfer of *Listeria monocytogenes* on Salami during Slicing

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ABSTRACT: *Listeria monocytogenes* has been implicated in several listeriosis outbreaks linked to the consumption of presliced ready-to-eat (RTE) deli meats, which has drawn considerable attention in regard to possible cross-contamination during slicing operation at retail and food service environments. Salami with 15% fat (a moderate fat content deli item) was used to investigate the transfer of *L. monocytogenes* between a meat slicer and salami slices and to understand its impact on food safety. A 6-strain cocktail of *L. monocytogenes* was inoculated onto a slicer blade to an initial level of approximately 3, 5, 6, 7, or 9 log CFU/blade (or approximately 2, 4, 5, 6, or 8 log CFU/cm^2 of the blade edge area), and then the salami was sliced to a thickness of 1 to 2 mm (case I). For another cross-contamination scenario, a clean blade was first used to slice salami loaf that was previously surface-inoculated with *L. monocytogenes* (approximately 3, 5, 6, 7, 8, or 9 log CFU/100 cm^2 area), followed by slicing the uninoculated salami loaf (case II). The salami slicing rate was maintained at an average of 3 to 4 slices per minute in all the tests. The results showed that the empirical models developed in this study were reasonably accurate in describing the transfer trend/pattern of *L. monocytogenes* between the blade and salami slices if the inoculum level was > 5 log CFU on the salami or blade. With an initial inoculum at 3 or 4 log CFU, the experimental data seemed to suggest a rather random pattern of bacterial transfer between blade and salami. The currently developed models are microbial load (n), sequential slice index (X), and contamination route dependent, which might limit their applications to certain conditions. However, the models may be further applied to predict the 3 or 4 log CFU level (and below) cross-contamination of salami slicing process. Considering only few data are available in the literature regarding food pathogen surface transfer, the empirical models may provide a useful tool in building risk assessment procedures.

Keywords: *Listeria*, modeling, salami, slicing, transfer

Introduction

In preparing sliced ready-to-eat (RTE) meat products such as ham, salami, bologna, and other restructured meat, a slicer is commonly used and probably as the last preparation process step before packaging or wrapping RTE foods. Those items are available in the supermarket refrigerated food section, either produced by brand names (mass production) or in store (made to order), and becoming more popular on demands. Sliced RTE products are also commonly sold by delicatessen and fast food restaurants, where a retail-scale slicer may be used on site for meal or sandwich preparations. The slicing machine, if not properly cleaned and regularly sanitized, can cause microbial cross-contamination. Since *Listeria monocytogenes* is a psychrotrophic pathogen and has been isolated from sliced RTE meats and caused outbreaks (CDC 2002), it is of special interest from a public health protection perspective to minimize potential food hazards. It is estimated that about 2500 cases of listeriosis occurred each year, resulting in 500 deaths, in the United States (Mead and others 1999). The outbreaks of listeriosis and their economical and public health impacts have been reported by ILSI Research Foundation/Risk Science Inst. (2005). However, even with precautions taken and regulations imposed, *L. monocytogenes* contamination in foods might still occur. A survey of 8 categories of RTE foods collected over 14 to 23 mo from retail markets in Maryland and northern California FoodNet sites showed that 577 out of 31705 (1.82%) samples were positive for *L. monocytogenes*. Among those, highly contaminated samples were luncheon meats and smoked seafood (Gombas and others 2003). The data on the prevalence and concentration of *L. monocytogenes* in packaged precut (slices or cubes) RTE meat products available in the Hellenic retail market in Greece indicated that 8.1% (17/209) of the products were positive, but the level of contamination was low, ≤10 CFU/g (Angelidis and Koutsoumanis 2006). The prevalence of *L. monocytogenes* in RTE meat and poultry, seafood, dairy products, and produce has been reported with published data collected in the retail and food service environments (Lianou and Sofos 2007).

For RTE meats with slicing being the last processing step, and no further intervention treatment prior to packaging, slicing becomes an important stage to monitor *L. monocytogenes* contamination during the industrial production of sliced RTE meat products. A study on cross-contamination of *L. monocytogenes* between processing equipment and deli meats found that the slicing did play an important role in microbial transfer from equipment to sliced meats. The degree of transfer correlated with the numbers of *Listeria* inoculated onto the slicer blade, where the inoculum levels were from 1 to 3 log CFU/g was reported by Lin and others (2006). Numerous publications on fate of *L. monocytogenes* in RTE meat are available, but information on transfer of foodborne pathogens from 1 surface to another contact surface is relatively rare, especially with modeling. Flores and others (2006) published the transfer coefficient models for *Escherichia coli* O157:H7 on contact surfaces between beef and high-density polyethylene. Recently, *L. monocytogenes* transfer studies in deli meat (Vorst and

others 2006; Sheen and Hwang 2008) and gravad salmon (Aarnisalo and others 2007) were reported. In these studies, the following 2 contamination scenarios were considered: (1) from an inoculated commercial round slicer blade edge (perimeter) to uninoculated delicatessen meats and salmon (case I); (2) from an inoculated product to an uninoculated product via the slicer blade, with different inoculum levels (case II). It has been shown that the cutting force, fat, and moisture contents were significant factors affecting *L. monocytogenes* transfer (Vorst and others 2006). Aarnisalo and others (2007) showed that the transfer of *L. monocytogenes* during slicing of gravad salmon was affected by initial inoculum level, temperature, and attachment time. They concluded that the total *L. monocytogenes* transfer count was lower when the inoculum level was lower (5.9 to 9.0 log CFU/blade), the temperature was cooler (0 °C, 10 °C, and room temperature) and the attachment time was longer (10 min and 2.5 h). A general exponential model was also developed to fit the data at different transfer conditions.

Using mathematical models to predict the transfer of *L. monocytogenes* between RTE meat/salmon and the slicer blade may assist in assessing the risk of cross-contamination during slicing. In this study, the transfer of *L. monocytogenes* from 1 contact surface to another for RTE deli meats with a delicatessen or restaurant type slicer was investigated. The objective was to develop a mathematical model to describe the surface cross-contamination for the slicing operation. Two cross-contamination routes for salami were studied for model development similar to cases I and II (Vorst and others 2006). Due to the complexities of parameter interactions and their impact on the transfer being not fully understood or well defined, the current study was limited to 1 food system (deli salami with 15% fat content). Other significant factors, including type of foods, operation parameters, microbe, and blade (type, size, speed, and so on), are discussed for future model development considerations.

Materials and Methods

Strains

A cocktail of 6 strains was used for the transfer study. A loopful of each strain was transferred from a stock culture stored at –80 °C into 10 mL of brain heart infusion broth (BHI, Becton, Dickinson and Co., Sparks, Md., U.S.A.) and incubated at 37 °C for 6 h (Sheen and Hwang 2008). A loopful of cell suspension of each strain was then separately transferred to 10 mL of BHI broth and incubated at 37 °C for 24 h. Each strain was plated to determine the cell counts and adjusted to obtain equal cell contribution in the cocktail with 0.1% peptone water before the final cocktail preparation. One milliliter of cell suspension from each strain was combined, and the mixture was further diluted with sterile 0.1% peptone water to the targeted level of *L. monocytogenes*.

Delicatessen slicer

A retail-scale, full 45° angle gravity-fed mechanical slicer (Model 3500, Globe Food Equipment Co., Dayton, Ohio, U.S.A.) was used for meat slicing. The slicer was equipped with a 305-mm (12-inch) diameter hollow ground knife (round blade) and operated at 300 revolutions per minute (rpm). The meat holding section was equipped with a 3-lb (1.36-kg) stainless steel end weight to deliver a consistent cut weight. The detailed configurations of the slicer can be found on the www.globeslicers.com, where a newer Model 3600 has replaced the old Model 3500 but maintained the similar structure/design.

Meat slicing and inoculation

The salami, locally made and purchased, was used in the experiment. The salami was made of pork, beef, and pork hearts. Other ingredients included water (added), corn syrup, salt, dextrose, spices, potassium lactate, flavoring, sugar, modified food starch, sodium diacetate, sodium phosphate, yeast, hydrolyzed soy protein, sodium erythorbate, and sodium nitrate. The appearance of the salami cross-section was not homogeneous and random black spots of seasonings were visible. The product contained 62% to 63% water and 13% to 15% fat. The average cross-cut surface was about 125 mm in diameter and the whole salami weighed about 5 kg. The whole salami was kept at 3 to 4 °C until used. Approximately 30 to 40 min was needed to completely slice a salami loaf. A digital thermometer (Series 396, Atkins Technical Inc., Gainsville, Fla., U.S.A.) was used to monitor the surface, and no apparent temperature change was noticed. The initial blade temperature was set at room temperature (approximately 21 °C).

To study the transfer of *L. monocytogenes* from a contaminated blade to meat (case I), the *L. monocytogenes* cocktails were evenly spread on each side of the blade. Each drop (total 10 drops of 10 μL/drop) was spread in 2 to 3 mm width and separated approximately 36° apart along the round blade edge. The same procedure was repeated for the other side of blade. The total area of blade edge inoculation was about 10 cm^2 of a 305-mm (12-inch) diameter and 2 to 3 mm width outer ring. The inoculated blade was placed in a laminar air flow laboratory hood for approximately 20 to 30 min to allow for the drying of the inoculum after which the slicer was assembled. The salami was cut into slices 1.5 to 2.0 mm in thickness and 15 to 20 g in weight. Each sliced sample was received/transferred directly into a stomacher bag (Spiral Biotech, Norwood, Mass., U.S.A.) for *L. monocytogenes* enumeration. Each salami slice was weighed and mixed with an equal amount of 0.1% peptone water and stomached for at least 2 min (Bag Mixer, Model 400, St. Nom, France). Sample dilutions (50 μL to 1 mL) were spread-plated in duplicate onto Modified Oxford Agar (MOX, Oxoid Ltd., Hampshire, U.K.) plates and incubated at 37 °C for 48 h, before typical *L. monocytogenes* black colonies surrounded by black precipitation zones were counted.

A 10 cm^2 area on the blade (both sides), blade protection cover, ham holding device, and liquid/waste receiving cup were swabbed with a cotton tip before slicing for enumeration of *L. monocytogenes*. The swab was placed in 9 mL of peptone water tube and vortexed for 10 s, and 1 mL of the sample was spread-plated onto duplicate MOX plates, and incubated for 48 h at 37 °C. This was to ensure that the whole slicer was free of *L. monocytogenes* before each experimental run. After each experiment, the slicer unit was disassembled and all removable parts were soaked in BacDown Detergent Disinfectant (Decon Labs Inc., Bryn Mawr, Pa., U.S.A.) diluted solution (1:10 in warm tap water) for at least 1 h at room temperature and then scrubbed and rinsed with hot water. The slicer surface was cleaned with 70% ethanol and air dried. The blade was further autoclaved (121 °C and 30 min) to destroy all *L. monocytogenes* after every use.

To study the transfer of contaminated meat to clean blade and then to noninoculated salami (case II), a slab of salami (30 mm thick) was inoculated with *L. monocytogenes* (20 × 10 μL, total count of 9, 8, 7, 6, 4, or 3 log CFU per slab) on all sides, except top and bottom surfaces. The 20 × 10 μL was spread on the cylindrical sides of the salami slab using a hockey stick with spread area about 100 cm^2. This ensured that most of the *L. monocytogenes* cells were transferred to the blade surface, compared to inoculation on all surface including top and bottom, and maximized the transfer for the subsequent slicing of the uncontaminated salami (Sheen

and Hwang 2008). The sample collection procedures and tests were the same as described previously (case I).

Sampling size of sliced salami

The proper sample size (number of slices collected) was determined by the transfer nature and was affected by factors including physical and chemical properties of the meat, the operational parameters (for example, blade type, size, slicing speed, and so on) and *L. monocytogenes* (strains) in the study. A trial-and-error approach was used to attain the most useful and meaningful results based on the research needs. For example, at low levels of *L. monocytogenes* inoculum (3 or 4 log CFU), the transfer result showed negative at around 70 to 100 slices. At higher levels of inoculum, 6 log CFU and up, about 200 to 350 slices were collected. Due to the large sample size, the salami slices collected from the 1st to the 40th slice were analyzed for *L. monocytogenes* counts for every slice, followed by every other 5 slices, that is, 45, 50, 55, to 100, then every 10 slices thereafter. The experiment was repeated 3 times for each combination of parameters.

Model development

TableCurve 2D version 5.01 (SYSTAT Software Inc. 2002) software was used to derive the models where the *L. monocytogenes* counts per salami slice was the dependent variable compared with slice sequence number as the independent variable. The models were empirical equations that described the microbial transfer pattern (distribution) in a series of slices. The models may be used to estimate the microbial number transferred to each salami slice for a specific amount of blade inoculum (case I) or salami contamination (case II) with limitations to the specified moisture and fat contents or in a close range. TableCurve 2D automatically search for hundreds of equations to fit a set of data and reported the selected models in an order of either coefficients of determination (r^2) or F-statistic from high to low order. Another important statistic result is the t-tests for all coefficients in a fitted model. Several factors were considered for the model selection in this study: F-statistic, t-test of each coefficient for parameter, simplicity, singularity, convergence, and r^2. Since the microbial transfer was expected to converge to zero after a large number of slice cuts, the model selected should satisfy this criterion. During the model development process, a "best-fit" model was selected to fulfill the following criteria: (1) describe the transfer counts with a decaying trend and approaching zero for large slice number; (2) show no singularity and divergence in prediction; (3) have fewer coefficients and parameters in the equation (a simple model); (4) $P > |t|$ (< 0.001) for all coefficients in the selected model; (5) have relatively high F-statistic [and with $P > F$ (< 0.0001)]; and (6) have an r^2 higher than 0.6 (preferable 0.7).

Results and Discussion

Surface transfer of *L. monocytogenes* from inoculated blade to salami (case I)

It was observed that the bacterial counts recovered from the first few slices were always 1 to 2 logs higher than the immediate following data points (an initially quick drop pattern), but approximately 3 logs less than the level of inoculum on the blade. The number of cells recovered from samples seemed to show a fluctuating exponential decay pattern as the slicing progressed. The 9 log CFU (9.1 ± 0.1) contamination level may need hundreds of slices to visibly demonstrate the trend although an exponential model fit the data well (Figure 1A). Figure 1B and 1C show the 7 log CFU (7.1 ± 0.2) and 6 log CFU (6.2 ± 0.2) per blade contamination transfer

results, respectively, which indicated a transfer pattern of an initial high *L. monocytogenes* transfer followed by sharply decreased, then, slightly increased, leveled off, and decreased again as the slicing proceeded. When a 5 log CFU (5.2 ± 0.1) per blade inoculation level was tested (Figure 1D), the transfer counts became less sensitive to slice number in a continuously decreasing transfer trend and approaching (or decaying to) zero in less than 100 salami slices. There is no positive count between slice numbers 19 and 27, and beyond 40th. For the 3 log CFU test, there was no systematic trend of transfer observed and no model available to describe the transfer pattern. A random and sporadic appearance of about 1 log CFU per slice of salami was observed, for example, 5 positive slices in the first 30 slices and 2 between 30th and 100th slice (or 7 *Listeria* positive slices per 100 slices collected). Lin and others (2006) conducted a study examining the cross-contamination of *L. monocytogenes* between processing equipment and deli meats (turkey, salami, and bologna) with 1, 2, and 3 log CFU blade inoculation and reported a similar low and random transfer result in the 3 log CFU case. In Lin's study, they also conducted enrichment tests for positive and negative confirmations. Their transfer results from a 3 log CFU per blade inoculation showed that *L. monocytogenes* was positive in 12/200 (6%), 7/200 (3.5%), and 1/200 (0.5%) for turkey, salami, and bologna, respectively. An enrichment test was not performed and not necessary for the modeling purpose, which is intent to describe the transfer trend, not the positive/negative detection. Overall, the number of contaminated slices compared to the number of salami slices collected (the initial 40 slices where every slice enumerated) was 5 (12.5%), 21 (52.5%), 36 (90%), 40 (100%), and 40 (100%) for inoculation levels of 3, 5, 6, 7, and 9 log CFU/blade, respectively.

In the current study, the detection limit was 1.48 log CFU at 15 g/sliced salami with 1:1 of salami to 0.1% peptone water added, or log (15 + 15) CFU. When 1 cell count and 1 zero count (not detected) on each plate of duplicate plating were observed, the limit became 1.18 log CFU/sliced salami, or log [(15 + 15)/2] CFU/slice. With 3 duplicate experiments, the limit could be as low as 0.70 log CFU as an average. When a 2 to 3 log reduction on the surface transfer at the high-level inoculums maintained, the available *L. monocytogenes* for surface transfer may be reduced to 0 to 2 log CFU at low level cases, which became not practical for cell enumeration count to fit the modeling purpose.

Models for case I

The generic equation or model that satisfies the model selection criteria for case I transfer scenario is shown below:

$$Y = A \cdot \text{Exp}\left(\frac{-X}{B}\right) \tag{1}$$

where Y is the log CFU count of the *L. monocytogenes* per salami slice and X is the salami slice number (an integer) of 1 series of slicing. A and B are coefficients (constants) derived from the regression analysis. Table 1 lists the A and B values for different levels of inoculation levels on the blade for case I.

The model selection criteria mentioned previously were carefully examined and fulfilled, except the r^2 value might be lower than 0.7 but above 0.6. The models predict that Y values approach to zero at large X without singularity. The reason that the cells recovered from the first few slices were always 2 to 3 logs below the inoculum level on the blade was not clear, but it was probably caused by the adhesion of *L. monocytogenes* onto the blade/food surface. Figure 1A to 1C also show an oscillation transfer pattern (in microbial counts) with its magnitude leveling off when slicing proceeded. A round blade operated at a certain rpm could

contribute to this observation. The cutting force, that is, tangential stress and radial stress, on the circular blade tends to push the microbes away and the salami surface (at contact with blade) tends to retain them during a revolution slicing, which could result in this "bumpy" pattern of microbial transfer distribution on the sliced salami.

To improve the overall data fitting, especially at the initial transfer portion (for example, the first 20 to 25 slices), an added 2-term exponential model (included in the TableCurve 2D model library) was selected, which can be viewed as a 2 first-order independent decay model, that is, $Y = k + a \operatorname{Exp}(-X/b) + c \operatorname{Exp}(-X/d)$. The regression statistical results showed improved data fitting between the initial predictions and experimental data and r^2, but much worse t-test (coefficients) and F-statistic (overall) results were observed. For example, in the 6 log CFU modeling, regression results showed the predicted initial value Y: 2.80 compared with 1.97 ($X = 0$); r^2: 0.69 compared with 0.6; $P > |t|$: < 0.05 compared with < 0.001; and F-statistic: 42.2 compared with 84.1 for 2-term compared with 1-term model, respectively. It was clearly shown that when the initial transfer rate is high, the 2-term model could better describe the initial transfer part but not the entire process. Due to the zero tolerance of *L. monocytogenes* in RTE foods, the food safety will be more concerned about the duration of the pathogen appears in the sliced salami. Therefore, the 1-term exponential model (1 first-order decay), Eq. 1, was selected for this study and further analyses.

The transfer of *L. monocytogenes* from inoculated salami to noncontaminated salami via clean blade (case II)

Salami inoculated with inoculum levels of 9, 8, 7, and 6 log CFU was used to examine the transfer of bacteria and model development. The results showed that there were slightly higher numbers of *L. monocytogenes* cells (0.5 log CFU/slice) transferred from blade to salami compared with those from the direct blade contamination (case I) at the same *L. monocytogenes* inoculation level (in total count). It is reasonable to assume that not all *L. monocytogenes* cells will attach to the blade, blade cover, and other slicer surfaces (for example, meat holding plate) during the contaminated salami slicing. However, a significant portion of *L. monocytogenes* was attached (or transferred) to the blade/slicer surface based on the *L. monocytogenes* counts from the slicing results (Figure 2A to 2D). The transfer results showed a similar decreasing pattern of *L. monocytogenes* on sliced salami in this scenario compared with case I; that is, the transfer curves may decay exponentially in both cases. With high inoculation levels at 9 (9.1 ± 0.1) and 8 log CFU (7.9 ± 0.3), a stable with slow-decreasing transfer was observed on the first 200 slices. Cells of *L. monocytogenes* may loosely attach on the contaminated salami surface which are easily transferred to blade, blade cover, and other slicer surfaces, then to the uncontaminated salami surface.

Another possibility to cause the *L. monocytogenes* to be more transferable was that a thin-film of salami (with 13% to 15% fat
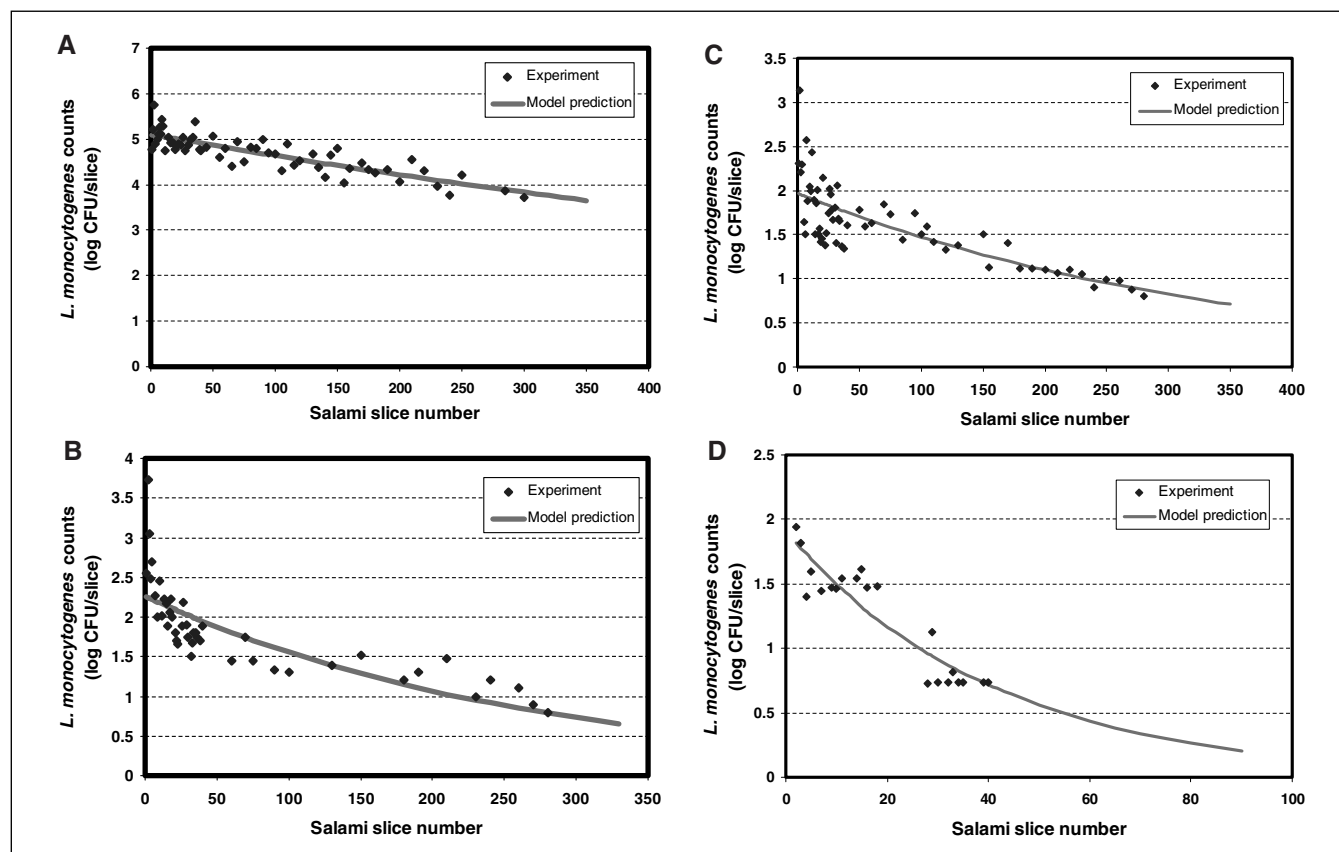
Figure 1 — (A) Transfer of *L. monocytogenes* (10^9 CFU/blade) (contaminated blade to salami slice). **(B)** Transfer of *L. monocytogenes* (10^7 CFU/blade) (contaminated blade to salami slice). **(C)** Transfer of *L. monocytogenes* (10^6 CFU/blade) (contaminated blade to salami slice). **(D)** Transfer of *L. monocytogenes* (10^5 CFU/blade) (contaminated blade to salami slice).

content) may have coated on the slicer surface (including blade) during the blade contamination procedure. When the attachment between *L. monocytogenes* and salami was not as strong as blade surface, the transfer became more feasible and higher potential of cross-contamination may occur. The transfer results of 3 log CFU *L. monocytogenes* inoculation showed up to 8 positives in 150 slices in a random mode (the worst case in 3 replicates). There is no satisfactory model to represent this type of transfer pattern.

Models for case II

An exponential model was also a good fit for this study, as expressed in Eq. 1. Similarly, an added 2-term exponential model was also carefully tested/examined for possibly better fit; the results showed the same conclusion as in case I. Figure 2A to 2D show the number of cells recovered from the slices at different levels of initial inoculum (9 to 6 log CFU) of *L. monocytogenes*. The model coefficients (A and B) are shown in Table 1 with regression *F*-statistic and r^2 values. When the model was used to predict the initial transfer count of slice at each level by setting X equal to 0, the results were lower than the experimental data. For example, the predicted initial slice shows 4.71, 3.11, 2.93, and 2.13 for 9, 8, 7, and 6 log CFU, respectively. The observed data were 5.21, 3.62, 3.41, and 2.60, which were about 0.5 log CFU above the estimated values. The surface *L. monocytogenes* transfer rate typically reduced faster at the beginning than the later process, which may cause the discrepancy between predicted and experimental data. Although the models may underestimate the initial transfer amount, the important application is to predict the potential cross-contamination where the model may provide.

The model, Eq. 1, developed to describe the surface transfer of *L. monocytogenes* on salami during slicing may be used to predict the possibility of *L. monocytogenes* appearance when the slice approaches a large number, for example, 1000. By inserting 1000, 2000, and 3000 into Eq. 1 of 7 log CFU, the Y value will be 0.195, 0.013, and 0.00086, respectively. The smaller the predicted number, the less possibility that pathogens will emerge.

Transfer model as a function of inoculation level (*n*)

The coefficient *A* and *B* values in Table 1 indicate that some simple relationship may exist between those coefficients and inoculation levels. It was difficult (with a great challenge) to perform data fitting analyses using equations/models with built-in (could be highly nonlinear) inoculation level, *n*; however, a more comprehensive model became feasible according to this observed correlation. For both case I and case II, the dependency of transfer count, *Y*, (in terms of *A* and *B*), on inoculation level, *n*, was derived using the Microsoft Excel spreadsheet program:

Case I:

$$A = 0.461 \, \mathrm{Exp}(0.255 \, n) \qquad r^2 = 0.880 \qquad (2)$$

$$B = 0.0215 \, n^{\wedge} 4.962 \qquad r^2 = 0.838 \qquad (3)$$

Case II:

$$A = 0.495 \, \mathrm{Exp}(0.244 \, n) \qquad r^2 = 0.933 \qquad (4)$$

$$B = 23.98 \, \mathrm{Exp}(0.413 \, n) \qquad r^2 = 0.949 \qquad (5)$$

By incorporating *A* and *B* into Eq. 1, the transfer model for case I becomes:

$$Y = 0.461 \cdot Exp(0.255 \cdot n) \cdot Exp\left(\frac{-X}{0.0215 \cdot n^{\wedge} 4.962}\right) \qquad (6)$$

And for case II,

$$Y = 0.495 \cdot Exp(0.244 \cdot n) \cdot Exp\left[\frac{-X}{23.98 \cdot \mathrm{Exp}(0.413 \cdot n)}\right] \qquad (7)$$

Using the nonlinear regression procedures available in SAS (1991) to examine Eq. 6 and 7, the results showed that both types of models also satisfied the criterion (Eq. 5) where the *F*-statistic, $P > F$ (< 0.0001).

Model predictions with low inoculation levels

It has been mentioned that with inoculation at level 3 or 4 log CFU, the surface transfer modeling becomes very challenging, if not impossible, due to the random transfer pattern (Aarnisalo and others 2007; Sheen and Hwang 2008). The observed 2 to 3 log initial microbial count reductions on surface transfer at the high-level inoculums further indicate the difficulty of modeling at low-level cases, which may imply only 0 to 2 log CFU available for surface transfer in the 3 to 4 log CFU levels. The modeling is to describe and predict the transfer trend (or probability in very low counts) and not to count the exact number of microbial cells on each sliced meat. Therefore, Eq. 6 and 7 may be applied to examine the *L. monocytogenes* surface transfer pattern for cases I and II during salami slicing processes at low contamination levels, respectively. The simulation results are presented in Figure 3 and 4. The inoculation level, *n*, can be assigned any positive real number for transfer simulations and predictions.

Other factors affecting the surface transfer

The following are the factors that can impact the transfer of *L. monocytogenes*, and some have been published in the literature: (1) the compositions of deli meat (moisture, fat contents, formulation, and so on), (2) the cut surface characteristics (texture, homogeneity) of deli meat, (3) the rpm of cutting blade, (4) the diameter of blade, (5) the sharpness (or profiles) and material of blade, (6) the back pressure from meat loaf (weight force exerted to contact blade surface by gravity and/or the end weight attachment), (7) the slicing speed (for example, slices per minute), (8) the contact angle, area, and slice thickness, (9) the microorganism (age, strain, inoculum size, capability to adapt different stresses, adhesion to surfaces, and so on), and (10) the environmental condition (for example, temperature and so on). The first 2 factors are the physical properties

Table 1 — Coefficients *A* and *B* for cases I and II cross-contamination transfer model, Eq. 1.

Case/level	A	B	F-statistic	r²
Case I				
9 log CFU	5.106	1045.365	148.98	0.72
7 log CFU	2.264	265.845	66.04	0.61
6 log CFU	1.970	343.448	84.10	0.60
5 log CFU	1.914	40.558	104.15	0.84
Case II				
9 log CFU	4.712	955.791	121.53	0.71
8 log CFU	3.111	739.821	116.53	0.70
7 log CFU	2.934	368.956	296.7	0.82
6 log CFU	2.128	304.272	73.11	0.62

of salami, whereas factors 3 to 8 are the operation parameters. Although not all the physical factors have significant impact on *L. monocytogenes* transfer, identifying and quantifying those important factors continue to be a challenge.

Mafu and others (1991) reported that *L. monocytogenes* (22 strains) were physicochemically characterized as hydrophilic microorganisms having a surface free energy of 65.9 mJ/m^2, which affects the cell adhesion on different contact surfaces. Atkins and Xu (2005) studied the cutting force in scissors and extended the application to curved blades. They concluded that the "slice/push ratio" (blade tangential speed to blade edge normal speed) had a strong influence on the cutting force that was not a constant with
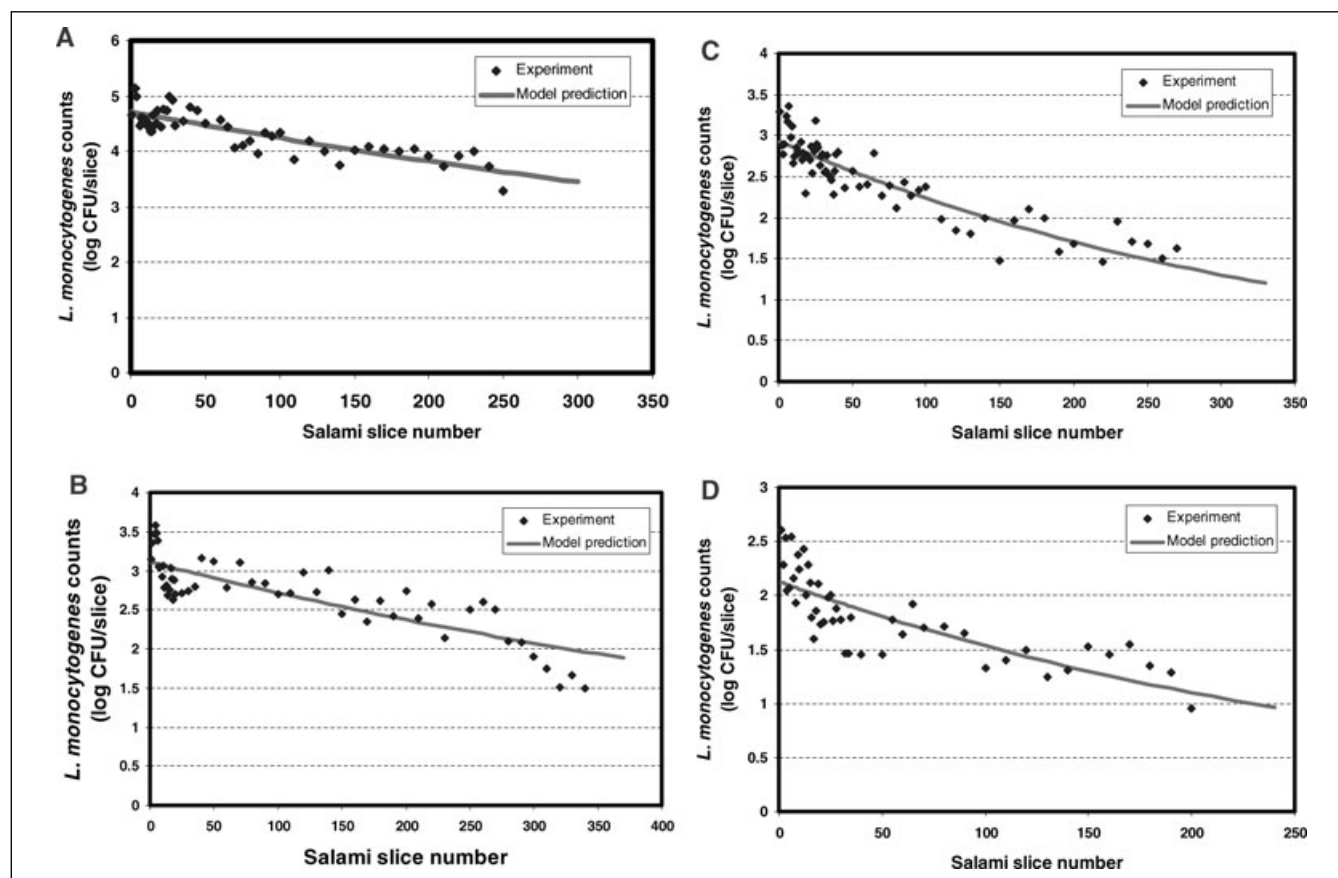

Figure 2—(A) Transfer of *L. monocytogenes* (10^9 CFU) (contaminated salami to clean blade to salami). (B) Transfer of *L. monocytogenes* (10^8 CFU) (contaminated salami to clean blade to salami). (C) Transfer of *L. monocytogenes* (10^7 CFU) (contaminated salami to clean blade to salami). (D) Transfer of *L. monocytogenes* (10^6 CFU) (contaminated salami to clean blade to salami).
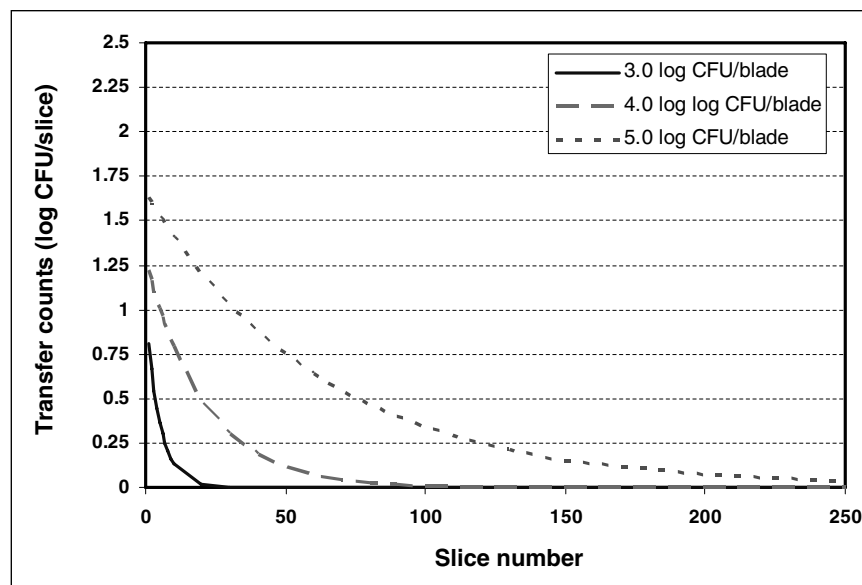

Figure 3—Transfer predictions using Eq. 6 with inoculation levels of 3, 4, and 5 log CFU for case I.
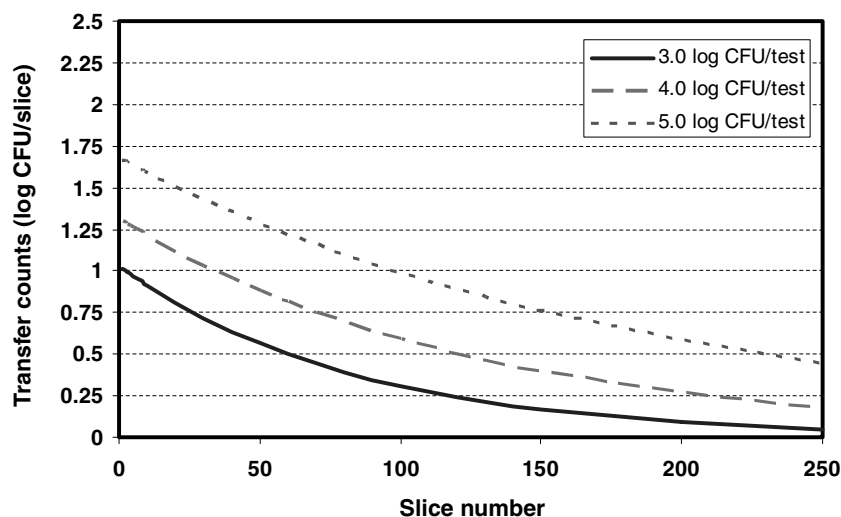
Figure 4—Transfer predictions using Eq. 7 with inoculation levels of 3, 4, and 5 log CFU for case II.

hand slicing and would be blade rpm dependent. The meat compositions also play an important role during transfer, especially the moisture and fat contents, which affect the salami and cut surface texture (Vorst and others 2006). Aarnisalo and others (2007) reported that the transfer was lower when the operation temperature was low and adhesion time was long in the salmon slicing. Arnold and Bailey (2000) reported that stainless steel surface finishes may impact the bacterial attachment and biofilm formation. Keskinen and others (2008) reported that *L. monocytogenes* having strong biofilm-forming ability can survive slicing better than weaker ones and also observed more microbial transfer on sliced roast turkey breast with 6-h attachment than 24-h attachment. Rodriguez and others (2008) studied the effect of surface roughness and stainless steel finish on *L. monocytogenes* attachment and biofilm formation. They concluded that *Listeria* initial adhesion (5.9 to 6.1 log CFU/cm^2) or biofilm formation (6.9 to 7.2 log CFU/cm^2) was not significantly correlated with surface roughness and there was no advantage for food sanitation of using electropolishing over mechanically finished stainless steel. The effect of temperature and growth media on *Listeria* attachment to stainless steel was investigated by Mai and Conner (2007). They found that cells maintained at 30 and 37 °C showed stronger attachment than at 4, 20, and 42 °C. Also, cells cultivated from rich medium have greater attachment than those from starved in the minimal medium.

The initial available *L. monocytogenes* counts on blade surface for transfer might be largely determined by the inoculum size and adhesion or attachment factors. Montville and Schaffner (2003) studied the cross-contamination between surfaces influenced by inoculum size and concluded that the inoculum size on the source and the amount of bacteria transferred must both be considered to accurately determine bacterial transfer rates. Furthermore, each targeted pathogenic microbe has its unique capability to survive the hostile environments and there also exist differences among the same population. Tasara and Stephan (2006) summarized an overview of the *L. monocytogenes* adaptation to the environmental stresses and the response mechanisms, which may provide some insights on how *L. monocytogenes* might survive the physical "shock" during slicing.

Conclusions

The transfer of *L. monocytogenes* cells from slicer to salami during slicing operation was simulated and modeled. The surface transfer was significantly affected by the inoculation level and con-

tamination route. In general, the higher the initial contamination level of *L. monocytogenes* on the blade, the larger the number of salami slices that were contaminated with *L. monocytogenes* during slicing. *L. monocytogenes* cells that were introduced onto the blade by salami remained on the blade for a slightly longer time than cells that were inoculated onto the blade. The empirical models developed from this study, as a function of both inoculation level and slicing number index, well describe the trend of *L. monocytogenes* transfer between the blade and salami slices with reasonable accuracy. The models may be further applied to predict the cross-contamination of salami slices with contamination levels of 3 or 4 log CFU where the experimental data were more difficult to collect and, therefore, not sufficient to support the model development. By using the models, the surface transfers due to low cross-contamination level may be clearly demonstrated. The empirical models may also provide a useful tool in building risk assessment procedures.

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